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Positive Temperature Coefficient of Breakdown Voltage in 4H-SiC PN Junction Rectifiers

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Abstract

It has been suggested that once silicon carbide (SiC) technology overcomes some crystal growth obstacles, superior SiC semiconductor devices will supplant silicon in many high-power applications. However, a positive temperature coefficient of breakdown voltage, a feature crucial to realizing excellent power device reliability, has not been observed in 4H-SiC, which is presently the best-suited SiC polytype for power device implementation. This paper reports the first experimental measurements of stable positive temperature coefficient behavior observed in 4H-SiC pn junction rectifiers. This research indicates that robust 4H-SiC power devices with high breakdown reliability should be achievable after SiC foundries reduce material defects such as micropipes, dislocations, and deep-level impurities.

Introduction

Theoretical appraisals of SiC power devices have suggested that once silicon carbide technology matures sufficiently to overcome some developmental obstacles, SiC may supplant silicon in many high-power electronic applications [1–3]. A property crucial to power device reliability is the type of breakdown that occurs in high-quality silicon power devices. Stable first breakdown in silicon exhibits a positive temperature coefficient of breakdown voltage that is due to the decrease of the mean free path of an electron when a crystal lattice is heated. If no other transport mechanism competes to destabilize a silicon junction during a constant voltage pulse (one that biases the diode into reverse breakdown), the breakdown current will decrease with the increase in breakdown voltage that occurs as the junction heats up. This property is crucial in preventing the formation of damaging hotspots and high-current filaments during first breakdown. Devices exhibiting negative temperature coefficient behavior could be destroyed by a transient glitch that temporarily biases a diode into the avalanche regime. This is because negative temperature coefficient behavior focuses and intensifies breakdown current at localized junction hotspots, forming high-current filaments that physically damage the device [4, 5].

Until now, previous *pn* junction rectifiers that are process compatible with commercial 6H- and 4H-SiC wafers (in which the current flows vertically through the wafer roughly parallel to the crystallographic *c*-axis) have exhibited a negative temperature coefficient of breakdown voltage [6–10]. Furthermore, it has been experimentally demonstrated that some 6H- and 4H-SiC rectifiers could not even reach their steady-state breakdown voltage when subjected to a single 0.2-μs pulse [11,12]. It is doubtful that SiC devices with unstable breakdown properties could be reliably incorporated into many kinds of power systems without cost penalties (additional overvoltage protection circuitry) and/or performance penalties (excessive reverse voltage derating).

Earlier measurements of SiC junctions with negative temperature coefficient breakdown may have reflected the presence of micropipes, dislocations, and deep-level impurity defects, all of which can be reduced or eliminated by improvements to SiC crystal growth. Given the importance of stable breakdown properties to the reliability of power devices, it is crucial to ascertain whether unstable breakdown is a fundamental property of SiC that would not be avoided by crystal growth improvements. In this work, we sought to fabricate and study SiC devices with minimum crystal imperfections in order to understand the true nature of breakdown in higher quality SiC junctions. Since crystal dislocation densities of SiC epilayers on commercial 6H- and 4H-SiC wafers are known to be on the order of 10^4 cm^{-2}, devices with areas less than 5×10^{-5} cm^2 were the primary focus of this work, so that around half should be free of micropipes and dislocations [13]. Furthermore, we employed a high-quality epitaxial SiC growth to minimize the presence of deep-level impurities [14].

Experiment

The SiC homoepilayer structure shown in figure 1 was grown by NASA Lewis on substrates cut from commercially available [15] n^+ 4H silicon-face SiC substrates polished 3° to 4° off the (0001) SiC basal plane. P^+n diodes with *n*-type dopings varying between 2.5×10^{17} and 1.5×10^{18} cm^{-3} (as measured by 1-MHz capacitance-voltage profiling) were produced by atmospheric-pressure chemical vapor deposition; these diodes were produced with Si/C atomic ratios of 0.16 in the nitrogen-doped and 0.09 in the aluminum-doped layers [14,16,17]. A 2000- to 3000-Å-

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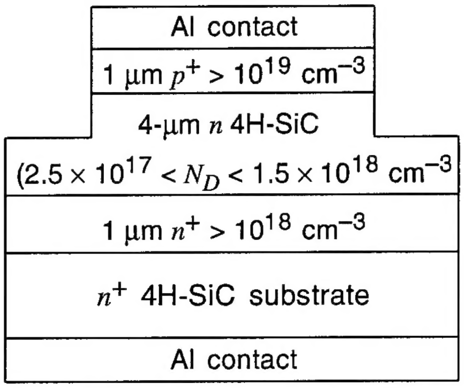

Figure 1. 4H-SiC *pn* junction diode cross section.

thick aluminum etch mask, which defined circular and square diode mesas ranging in area from 7×10^{-6} cm^2 to 4×10^{-4} cm^2, was applied and patterned by metal liftoff. Diode mesas were defined by etching to a depth of approximately 2 to 3 μm: reactive ion etching was used with 90% CHF_3 : 10% O_2 at 400 W rf, and a chamber pressure of 150 mTorr. The etch mask was employed as the topside device contact, while blanket-deposited aluminum served as a backside contact.

All measurements were carried out in the dark at room temperature on a probing station. Figure 2 shows a typical dc I-V (current-voltage) characteristic obtained from a diode with n-layer doping of 4.3×10^{17} cm^{-3}. Any diode that showed leakage current before breakdown or an unsharp nonvertical breakdown knee was excluded from further testing. The dc breakdown voltages observed in this work were consistent with 4H-SiC *pn* junction dc breakdown voltages reported in the literature [18].

Because self-heating can cause rectifier junction temperatures to deviate significantly from ambient temperatures, we did not rely on curve-tracer measurements recorded as a function of ambient temperature to ascertain the temperature variation of breakdown voltage. Instead, we recorded the time evolution of device current and voltage during the breakdown process. As the device self-heated during the application of a breakdown bias pulse, the sign of the breakdown voltage temperature coefficient was determined from the voltage and current transient waveforms [4,5]. A positive temperature coefficient was observed when the diode voltage increased with the decrease in diode current as the device was heated by the bias pulse. Negative temperature coefficient behavior was observed when diode voltage decreased as diode current increased during the pulse.

The calibrated charge-line circuit used to conduct pulsed measurements is described elsewhere [11]. This circuit reverse biased the diodes by generating rectangular-shaped pulses of 200-ns width (with ~1 ns risetime/falltime). The

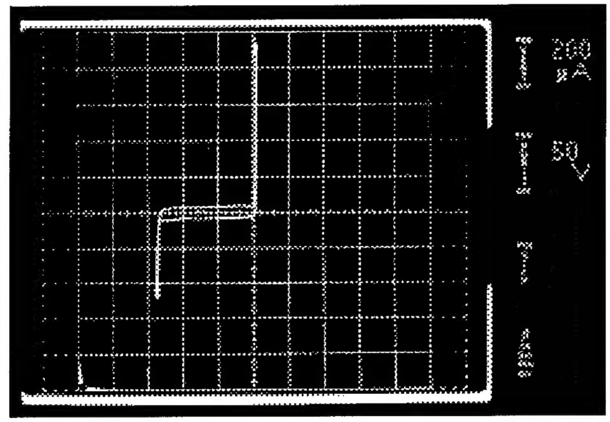

Figure 2. Curve-tracer measured I-V characteristics of 4.42×10^{-5} cm^2 circular 4H SiC *pn* junction rectifier recorded at room temperature ambient.

pulses were manually triggered in a single-shot mode. The transient device voltage ($V_D(t)$) and current ($I_D(t)$) waveforms were simultaneously recorded and stored for each applied pulse on a dual-channel digitizing oscilloscope. The devices under test were checked between pulses for any changes in dc I-V characteristics.

Figure 3 shows a series of device voltage and current waveforms as the input pulse amplitude was increased. All transient data in figure 3 were taken from the same 4H-SiC diode whose dc characteristics are displayed in figure 2. No measurable current (aside from displacement current spikes at the rising and falling edges of the pulse) was observed for any input pulse amplitudes below the dc measured breakdown voltage. At input pulse amplitudes larger than the dc measured breakdown voltage, significant conduction current flow is observed, while $V_D(t)$ becomes noticeably smaller than the input pulse amplitude because of clamping. The sign of the breakdown voltage temperature coefficient could not be ascertained from the relatively flat-topped voltage and current data shown in figure 3(a), since the combination of self-heating and/or temperature coefficient was too small to be observed. However, data taken at larger pulse amplitudes (fig. 3(b) and 3(c)) clearly exhibit the classically stable and reliable silicon-like behavior of positive temperature coefficient of breakdown voltage. As the device heated up during the 200-ns pulse duration, the breakdown current through the device $I_D(t)$ decreased, while the voltage across the device $V_D(t)$ increased. Approximately 2.5 A of peak conduction current is observed in figure 3(c), which corresponds to a current density of more than 50,000 A/cm^2. Despite severe physical damage to the contact metallization that prevented transient testing at even larger pulse amplitudes, the dc measured reverse I-V characteristics of the diode remained unchanged from the initial characteristics shown in figure 2.

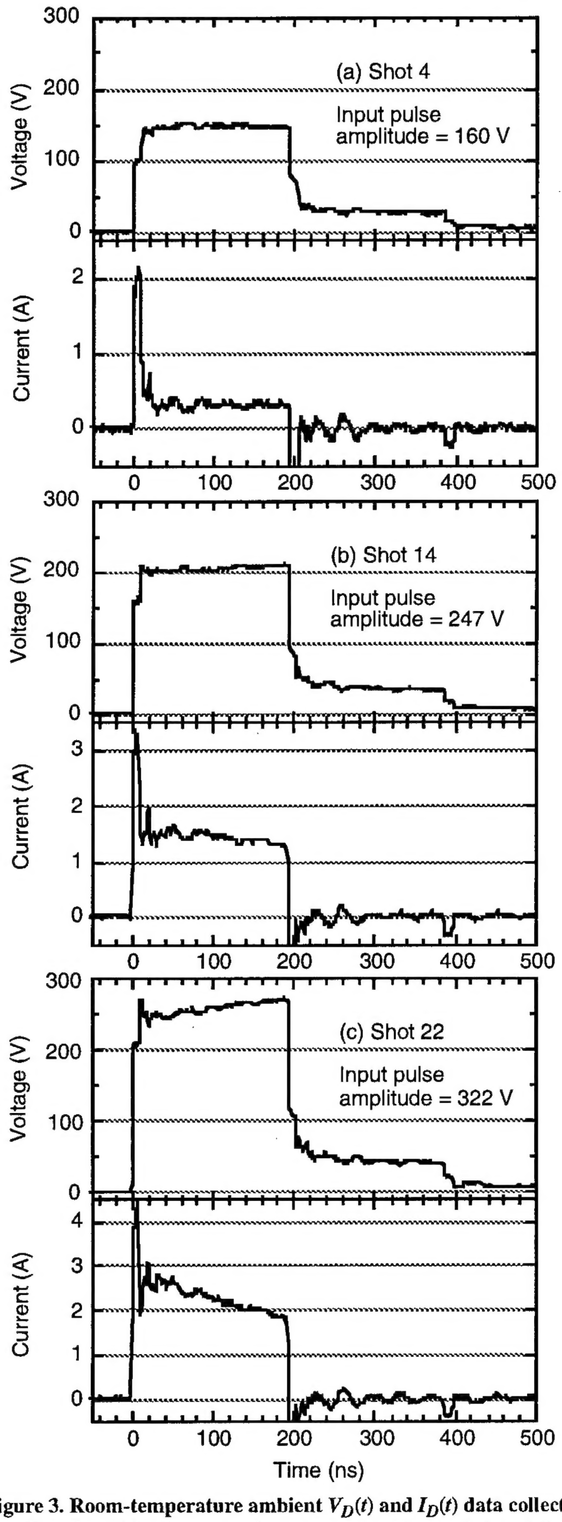

Figure 3. Room-temperature ambient $V_D(t)$ and $I_D(t)$ data collected on 4H-SiC rectifier (same device as fig. 2) subjected to breakdown bias pulses from a charge-line circuit, showing positive temperature coefficient of breakdown voltage: as device heats up over 200-ns pulse, breakdown current flow $I_D(t)$ through device decreases, while voltage $V_D(t)$ across device increases in (b) and (c). Current spikes at rising and falling edges of pulse are due to displacement current, while peak conduction current of ~2.5 A corresponds to a current density >50,000 A/cm^2.

As of this initial report, 10 small-area diodes (out of 13 that demonstrated dc *I-V* characteristics of sufficient quality to warrant pulse testing) exhibited positive temperature coefficient breakdown. In most positive temperature coefficient devices, contact failures prevented pulse testing from reaching sufficient pulse amplitudes for junction failure to be observed. Six 4H-SiC diodes larger than 1×10^{-4} cm^2 were pulse tested, and all exhibited negative temperature coefficient breakdown behavior leading to junction failure. Junction failures (as opposed to contact failures) were observed on all negative temperature coefficient devices tested, regardless of device size.

Summary

By studying diodes with junction areas small enough to avoid dislocations and micropipes, we have observed a positive temperature coefficient of breakdown voltage in 4H-SiC rectifiers. The experimental results described above are consistent with the hypothesis that defects can negatively affect the breakdown properties of SiC *pn* junctions. The impact of deep-level impurities and dopant carrier freezeout, which have also been suggested as possible contributing factors to unstable SiC breakdown behavior [6,11,12], remains an open question for investigation. Nevertheless, these results show that *pn* junction rectifiers with reliably stable breakdown properties can be obtained in 4H-SiC. This study indicates that robust 4H-SiC power devices with the same high reliability as modern silicon power devices should be achievable after SiC technology matures enough to greatly reduce defects such as micropipes, dislocations, and deep-level impurities in commercial SiC wafers and epilayers.

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